

December 4, 2006 1:35

WSPC - Proceedings Trim Size: 9in x 6in fushimi-idm

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## WIMPs search by exclusive measurements with thin multilayer NaI(Tl) scintillators (PICO-LON)

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The WIMPs search project PICO-LON has been started with multilayer thin NaI(Tl) crystals. The thin (0.05cm) and wide area (5cm×5cm) NaI(Tl) crystals was successfully developed. The performances of thin NaI(Tl) scintillator was measured and they showed good energy resolution (20% at 60keV) and good position resolution (20% in 5cm×5cm wider area).

*Keywords:* WIMPs search, Thin NaI(Tl)

## 1. Introduction

Dark matter search are one of the most important subjects in nuclear- and particle-physics. The particle candidates for cosmic dark matter is a key subject not only astrophysics but also particle physics since the particle candidates for dark matter is proposed by various models of the beyond standard model.

The components of the universe has been clearly understood by many cosmological observations. [1–3]. Since, the most of the matter in the universe should be the cold dark matter, searching for WIMPs (Weakly Interacting Massive Particles) is quite important. Recently, a direct empirical evidence for dark matter in a galaxy has been reported [4,5]. The dark matter in the galaxy has become quite ensuring. One of the most promising candidate for WIMPs is SUSY neutralino, which interacts with the matter via only weak interaction.

The processes for WIMPs-nucleus interaction are schematically illustrated in Fig.1. In Fig.1(a), the scattering amplitude is summed coherently

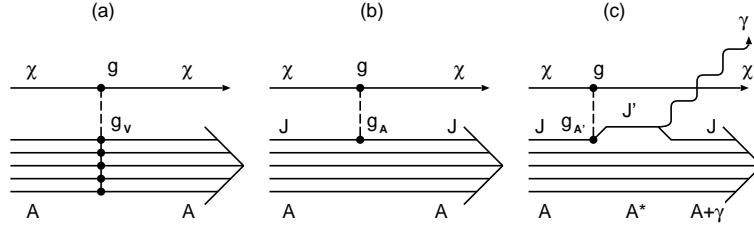


Fig. 1. Feynman diagrams for WIMPs-nucleus interaction. “A” and “χ” means the nucleus and the WIMPs. (a) Spin independent elastic scattering (SI). (b) Spin dependent elastic scattering (SD). (c) Spin dependent inelastic scattering (EX).

over all the nucleon. Thus the scattering cross section is coherently enhanced by the factor  $A^2$ , where  $A$  is the mass number of the target nucleus. In Fig.1(b), only one nucleon which carries the nuclear spin contributes the cross section. Thus the cross section is a few orders of magnitude smaller than that of the previous case. The cross section depends on the nuclear spin-matrix element  $\lambda^2 J(J+1)$ . and has a large ambiguity because this matrix element has a large model dependence for the heavy nuclei [6]. In Fig.1(c), the target nucleus will be excited to the low lying excited state, which is followed by the gamma ray emission. This process is arisen only if the WIMPs particle has enough kinetic energy. In this case, the matrix element is measured precisely by the nuclear de-excitation [6–8]. Thus the

model dependence of the cross section is much smaller than the cross section of the SD case.

The segmentation of the detector is shown to be the best way to enhance the position sensitivity [9]. Coincidence measurements of nuclear recoils and  $\gamma$  rays for the inelastic excitation of  $^{127}\text{I}$  enhanced the sensitivity using the highly segmented NaI(Tl) detector. Recently, ionized atomic electrons and hard X rays following WIMPs-nuclear interactions have been shown to be useful for the exclusive measurement of nuclear recoils from the elastic scatterings of WIMPs off nuclei [10,11]. On the other hand, the background events have their own characteristics of timing and spatial profiles. Because the event rate due to the background is reduced by segmentation, a probability of the accidental coincidence of individual background events is vastly reduced.

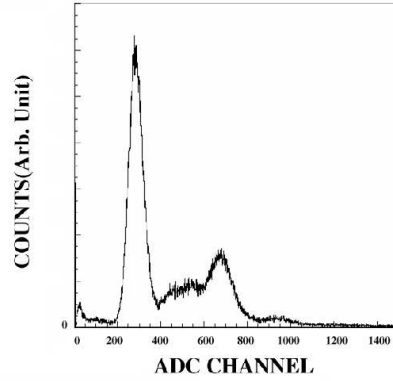
It has been shown that piling up many thin scintillators enhances the sensitivity for WIMPs search [9]. The highly sensitive detector system PICO-LON (Planar Inorganic Crystals Observatory for LOw-background Neutr(al)ino) has been developed. It consists of many thin NaI(Tl) crystals whose thickness is 0.05cm. Recently, PICO-LON-I which was made up three crystals of thin (0.05cm in thickness) and wide area (6.6cm $\times$ 6.6cm) NaI(Tl) crystals has been developed. PICO-LON-II which was made up sixteen crystals of thin NaI(Tl) has been also developed. In this report, we describe the excellent performance of a single plate of thin NaI(Tl) which is the foundation of PICO-LON system.

## 2. The performance of thin NaI(Tl) scintillator

The performance of the thin NaI(Tl) scintillator was measured by irradiating a thin NaI(Tl) crystal whose dimension was 5cm $\times$ 5cm $\times$ 0.05cm with low-energy  $\gamma$  rays and X rays. The scintillation photons were collected at the four edges of the NaI(Tl) crystal using four photomultiplier tubes (PMTs), which were provided by Hamamatsu Photonics (R329-P).

The gamma rays and X rays were irradiated isotropically on the wider surface of the NaI(Tl) plate. Each PMT output signal was individually input into four discriminators. The threshold of the discriminators was set above that of the single-photoelectron signal; the corresponding hardware energy threshold was 0.8keV. The four PMT outputs were individually converted to digital data using a charge integrating analog-to-digital converter (RPC-022). The total charge outputs of the PMTs were summed event-by-event using an off-line analyzer.

The resulting photon outputs are shown in Fig.2. In the pulse height

Fig. 2. Pulse height spectrum of  $^{133}\text{Ba}$ .

spectrum of  $^{133}\text{Ba}$ , high-energy gamma rays of energies above 200keV were not clearly observed because the detector was too thin to absorb the gamma rays. A photoelectric peak of 81keV and the corresponding X ray escape peak were observed at approximately 670ch and 500ch, respectively. The prominent peak at approximately 300ch was due to the K-X rays of cesium. Note that the small peak due to the low-energy L-X rays of cesium is observed approximately 30ch. It is important in the search for WIMPs to be able to observe low energy, and the present results correspond to the energy threshold being 2keV. The results showed that the thin NaI(Tl) scintillator displays great promise in the search for WIMPs.

The energy resolutions at FWHM (Full Width at Half Maximum) were calculated from the peaks and are shown in Table 1.

Table 1. Energy resolutions for low-energy photons at FWHM. The calculated number of photoelectrons (P.E.) is listed in the fourth column. [12]

Source	Energy (keV)	$\Delta E/E$ (FWHM)	# of P.E.
$^{133}\text{Ba}$	81	0.17	197
$^{241}\text{Am}$	60	0.20	143
$^{133}\text{Ba}$	31	0.28	71
$^{57}\text{Co}$	14.4	0.40	35

The scintillation output has good linearity up to 120keV. From the pulse height spectra, the low energy threshold was found to be 2~3keV. The energy equivalent to a single photoelectron was also calculated using

the photoelectron number  $N$ . The energy threshold of approximately  $2\sim 3\text{keV}$  corresponds to  $4\sim 5$  photoelectrons. The results showed an excellent performance that is in accordance with the required performance for the advanced stage of the experiment.

The position resolution for the thinner directions is as good as  $0.05\text{cm}$  because of the segmentation of the detector. Moreover, the position resolution for other directions was tested. Because the largest area has dimensions of  $5\text{cm}\times 5\text{cm}$ , good position information in the wider area enhances detector sensitivity. Position information was obtained by analyzing the ratio of the number of photons collected on the opposite sides of the detector. Precise position information on the largest area of the thin NaI(Tl) scintillator is important to ascertain the property of the events. By piling up the thin NaI(Tl) scintillator, the tracking of radiation such as cosmic rays and the multiple Compton scattering of photons is reconstructed precisely.

A collimator for low-energy  $\gamma$  rays was made of  $1\text{cm}$ -thick lead brick with nine holes with a diameter of  $2\text{mm}$  was used for position measurement. An  $^{241}\text{Am}$  source was placed at the top of each hole. Position determination analysis was performed using  $60\text{keV}$  gamma rays from  $^{241}\text{Am}$ . The position resolution was calculated to be approximately  $1\text{cm}$  in FWHM [12].

### 3. Estimated sensitivity for WIMPs

The case of inelastic scattering the nuclear spin-matrix element is experimentally deduced from the nuclear transition probability, consequently, the precise exclusion plot with small model dependence is obtained. The estimated sensitivity for SD type WIMPs is shown in Fig.3. It is shown that the high sensitivity is expected by the small amount of NaI(Tl) crystal.

### 4. Future prospects

Test experiment with the three-layer NaI(Tl) detector (PICO-LON-I) has been performed at surface laboratory at Tokushima. The PICO-LON detector will be installed into Oto Cosmo Observatory in the south of Nara prefecture where is  $150\text{km}$  east from Tokushima and  $100\text{km}$  south from Osaka.

Oto Cosmo Observatory is covered with thick rock whose thickness is about  $1200\text{m.w.e.}$  [13]. Thus the flux of cosmic ray is reduced by a factor of  $10^{-5}$  [14]. The most serious origin of low energy background is  $^{222}\text{Rn}$  in the air. Since the tunnel is opened at both ends and strong wind is running always, the concentration of Rn in the tunnel is the same as the one out

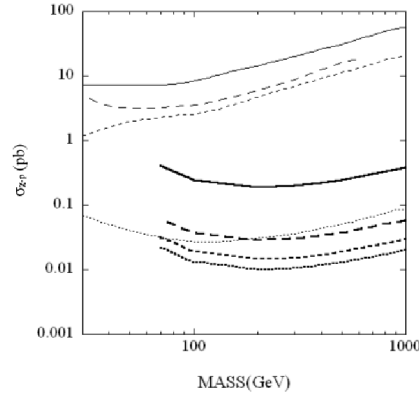


Fig. 3. Thick lines are the expected sensitivity for SD type WIMPs. The solid, long-dashed, sort-dashed and dotted lines are the expected sensitivity by 16, 256, 1024 and 2176 modules of NaI(Tl) array. Thin lines are results of CRESST (solid line), DAMA LXe (long-dashed line), ELEGANT V at OTO (short-dashed line) and the expected sensitivity by NAIAD (dotted line). [9]

of the tunnel. The measured Rn concentration in the air in the laboratory was measured by highly sensitive Rn monitor which can measure above 5mBq/m<sup>3</sup>.

PICO-LON-I and PICO-LON-II will be installed into the shield with the 10cm thick OFHC(Oxygen Free High Conductive Copper) and 15cm thick old lead, which was used for the shield of ELEGANT V.

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